Robust CO$_2$ Plume Imaging using Joint Tomographic Inversion of Seismic Onset Time and Distributed Pressure and Temperature Measurements

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Akhil Datta-Gupta
Texas A&M University
(collaborator: Srikanta Mishra, Battelle Memorial Institute)

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Presentation Outline

• Why are we doing this?
  – Benefits to the program
• How are we doing this?
  – Project overview and methodologies
• Accomplishments to date
  – Application to a post-combustion CO$_2$ WAG Pilot
• Summary and next steps
Benefit to the Program

• Program goals being addressed
  – Development of modeling and monitoring methods, tools, technologies that improve the certainty about the position of the CO₂ plume over time

• Project benefits statement
  – Provide a practical & cost-effective methodology for CO₂ plume delineation using routine pressure/temperature measurements + geophysical monitoring
  – Facilitate (near) real-time monitoring of CO₂ plume migration in field projects needed to meet current regulatory requirements
Project Overview:
Goals and Objectives

- Develop and demonstrate a rapid and cost-effective methodology for spatio-temporal tracking of CO$_2$ plumes during geologic sequestration
  - *Pressure and temperature tomography*: Use pressure & temperature arrival time data to infer spatial distributions of CO$_2$ plume
  - *Integration of seismic onset time*: Improve the seismic monitoring workflow through the integration of ‘onset’ times
  - *Joint Bayesian inversion and field validation*: Efficient Bayesian framework for probabilistic data integration validated using data from ongoing field projects (Petra Nova Parrish CCUS project, Texas)
Methodology
CO₂ Plume Imaging: Key Elements

• Recasting Fluid Flow Equations as Tomographic Equations
  – High frequency asymptotic solution

• Utilization of the Seismic Onset Time Concept

• Parsimonious Representation of Geologic Heterogeneity
  – Ill-posed inverse problem, needs regularization
  – Image compression via basis functions

• Data Integration and Image Updating
  – Multi-objective optimization and Inverse Modeling
Methodology

Asymptotic Approach: Fluid Fronts vs. Wave Fronts *

* Fatemi and Osher, 1995; Vasco and Datta-Gupta, 1999; 2016

- High frequency solution to the flow and transport equation mimics the one usually found in wave propagation
- We can exploit the analogy between the propagating fluid front and a propagating wave
- The trajectories or flow paths associated with the fluid front are similar to rays in seismology/optics
- Provides an efficient formalism for plume imaging using reservoir dynamic response
Methodology
Asymptotic Solution: Diffusivity Equation

• Diffusivity equation in heterogeneous medium

\[ \phi(x) \mu c_t \frac{\partial P(x,t)}{\partial t} = \nabla \cdot (k(x) \nabla P(x,t)) \]

- Transform to Fourier domain

\[ \phi(x) \mu c_t (-i\omega) \tilde{P}(x,\omega) = k(x) \nabla^2 \tilde{P}(x,\omega) + \nabla k(x) \cdot \nabla \tilde{P}(x,\omega) \]

• High frequency asymptotic solution leads to a propagation equation for pressure ‘front’:

\[ \sqrt{\alpha(x) |\nabla \tau(x)|} = 1 \]

where \[ \alpha(x) = \frac{k(x)}{\phi(x) \mu c_t} \]

Eikonal Equation

*The Eikonal equation can be solved efficiently using the Fast Marching Method (Sethian, 1996)*
Methodology
Solution to Eikonal Equation

- **Fast Marching Method**: efficient method to solve the Eikonal equation (Sethian 1998, 1999)
- **Dijkstra’s Method** (1959): computing the shortest path on a network
- **Single-pass**: solution can be constructed sequentially from small $\tau$ to large $\tau$

\[ \delta \tau(x) = \sqrt{\frac{\phi(x) \mu c_i}{k(x)}} \delta r \]

*Technology used in Google Maps*
Methodology

Pressure ‘Front’ Propagation

0.01 Day
Methodology
Pressure ‘Arrival Time’ Tomography
(He, Dattagupta, Vasco, 2006; Brauchler et al., 2007; Hu et al., 2015)
Methodology
Temperature Tomography

• Analogous Approach to Pressure Tomography
• Assumption – The diffusive time of flight gradients are aligned with temperature gradients
  – 3D to 1D equation for temperature propagation
• Proof of concept presented (SPE Journal, Dec. 2016)
Methodology
Seismic Monitoring via Onset Times

Two-Way Time Shift Maps: Peace River (Hetz et al., 2017)
Methodology
Onset Time Map: Better Representation of Time Lapse Seismic Data

Reduces multitude of time-lapse surveys into a single set of onset time map
Methodology

Time Shift Maps to Onset Time Map

- The calendar times at which geophysical observations begin to deviate from their initial or background value (Vasco, 2015)
Methodology

Seismic Monitoring Using Onset Time

- Efficient integration of frequent time-lapse seismic surveys through substantial data reduction
- More robust: Less sensitivity to petroelastic model compared to amplitude inversion
- Rapid convergence: quasilinear inverse problem

Applicability to infrequent seismic surveys needs to be investigated
Methodology

Data Integration and Model Updating: Issues

- Diverse Data Types
  - Scale, resolution and precision
  - Potentially conflicting

- Poorly constrained
  - Sparse data, large parameter space

- Multi-scale, Multi-objective Inverse Problem
  - Pareto Optimal Solution
Accomplishments to Date: Year 1

• CO₂ Plume Tracking at Petra Nova CCUS Pilot – Project
  – *Fuel* 255 (2019) 115810

• Saturation Imaging Seismic Onset Time: Impact of Survey Frequency
  – *SPE 196001* (ATCE 2019)

• Application of ensemble learning for machine-learning based data integration
Background: Petra Nova CCUS Project

- World’s largest post-combustion CO₂ capture, EOR and storage project
- NRG/JX Nippon partnership
- Captures more than 90% of CO₂ from a 240 MW flue gas stream (~ 5,000 tons of CO₂ per day)
- Captured CO₂ is utilized for EOR
- 60 MMSTB of oil is estimated to be recoverable from EOR operations
West Ranch Field 98-A CO2 Pilot
September 2012

- CO2 Pilot conducted in center of 98-A
- 16 acre inverted five-spot
- Single injector, four producers and two observation wells
- 230MMSCF CO2 injected for 20 days followed by water
- Clear oil response observed in two producers

Goal: Infer CO₂ plume movement based on the production response and CO₂ breakthrough
Previous Work: Field Model Calibration

(SPE Reservoir Engineering, January 2019)

Reservoir Model

Size: 10km x 5km
Thickness: 140ft
Geologic Grid: 253 x 212 x 140
Active Cells: 3,000,000
Perm Range: 0.5 – 40,000mD (Very heterogeneous)
• >120 wells drained over a period over 75 years
• No well completion data; limited well production data

Hierarchical Model Calibration

Next Steps
• Initialize pilot model from calibrated field model
• Integrated pilot production data
• Optimize CO₂ EOR design, as an optimal parametric design for entire field
Sector Model from Full Field Model

- Fully compositional model
- Pilot model initialized from the full-field model
- Boundary fluxes from full field model were imposed
Model Parameterization & Objective Function

\[ \text{Objective} = \ln(\text{WOPR\_Misfit}) + \ln(\text{WGPR\_Misfit}) + \ln(\text{WWPR\_Misfit}) + \ln(\text{WBHP\_Misfit}) \]
Model Calibration Results: CO₂ Mole Fraction

Graphs showing the model calibration results for CO₂ mole fraction at different locations (PWRA473, PWRA487, PWRA332, PWRA602) over time (09/01/12 to 11/20/12). The graphs compare observed data, CO₂ injection period, initial model response, GCT-calibrated model response, and GTTI-calibrated model response.
CO₂ Recovery Comparison

![Graph showing CO₂ recovery comparison](image)
Model Validation: Saturation Logs Comparison

- **600** is the Injector
- **473, 487, 602** and **332** are producers
- **314** and **601** are monitor wells
Saturation Logs Comparison: Well 314
Saturation Logs Comparison: Well 601

OBSERVED

INITIAL

UPDATED
CO$_2$ Plume Profile Comparison
Next Steps

- Development and testing of temperature tomography based plume detection for CO2-oil-gas-brine-systems
- Development and testing of joint inversion of temperature and pressure data for plume detection for CO2-oil-gas-brine-systems
- Further refinement of seismic onset time based inversion: survey frequency and attribute selection
- Field validation of the numerical tomographic inversion using data from ongoing CO$_2$ injection projects (e.g., Petra Nova CCS)
BACKUP
Expected Outcomes

- Advanced CO\textsubscript{2} plume mapping protocols using novel forward and inverse modeling techniques to:
  (a) reduce cost and uncertainty
  (b) satisfy regulatory requirements
  (c) provide continuous monitoring and long-term durability
  (d) cover a large area with improved accuracy

- **Key elements** are:
  (a) novel pressure and temperature tomography using the Fast Marching Method (FMM)
  (b) analysis of time lapse seismic data using a novel ‘seismic onset time’ approach to detect fluid front propagation
  (c) data assimilation and uncertainty assessment
  (d) field validation of the methodology
Methodology

Arrival Time of Pressure ‘Front’

Injection

Observation

\[ q(t) \] \[ p(t) \]

\[ \frac{dq}{dt} \] \[ \frac{dp}{dt} \]

Arrival Time of Pressure Front
Onset Time is Less Sensitive to the Petro Elastic Models

Velocity as a function of saturations for different averaging methods

Seismic response over the first 85 days of the CSS (Top View)

Time Shift

Onset Time

Velocity as a function of saturations for different averaging methods

Seismic response over the first 85 days of the CSS (Top View)
West Ranch Field: Background

- Highly heterogeneous (Fluvial Sand)
- Perm Range: 0.1 – 40,000 (mD)
- Severe vertical permeability anisotropy due to intermediate shale barriers (Dykstra-Parsons coefficient > 0.9)
- >120 wells drained for a period over a 75 years